INL/CON-24-77086-Revision-1

Thermal Gradient and Neutron Irradiation Experiment Design for Fusion Reactor Materials in the Advanced Test Reactor

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Changing the World's Energy Future

Michael Jason Worrall, Daniel B Chapman, Ryan Christopher Sandbek, Hanns Anton Gietl, Nicolas E Woolstenhulme, Jason V Brookman

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Dr. Michael Worrall
Idaho National Laboratory

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Outline

- The need for experimental data
- Temperature targets
- NITE conceptual design
- ATR overview & the problem with thermal test reactors
- B10 doping for He production
- Neutronic results
- Thermal results
- Summary
- Future/Ongoing Work

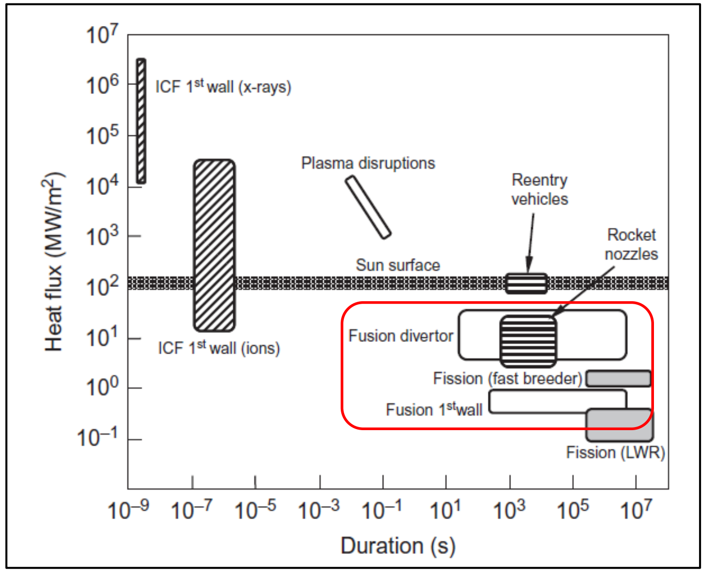
The Need for Experimental Data on Plasma-Facing Materials

- Tungsten (W) is currently considered as the most promising Plasma-facing material (PFM) for the first wall and divertor in a fusion reactor.
- Irradiation of PFMs in a prototypic fusion environment is not readily available, so fusion environments must be approximated using other means (e.g., ion beam irradiation, thermal test reactor irradiation)
- Irradiation of fusion relevant materials in a thermal test reactor is not new
  - e.g.: The U.S.-Japan collaboration irradiated W specimens in HFIR for several years. The latest HFIR irradiation campaign (RB-19J) surrounded W with a gadolinium liner for thermal neutron shielding. The specimens were irradiated up to 0.74 displacements per atom (dpa) at up to 1200 ˚C[1].
- However, such tests typically focus on approximating a single aspect of the fusion reactor (e.g., fast fluence, temperature, damage)
- **Synergistic tests that combine multiple aspects are necessary to understand the complex interactions that occur in a fusion reactor**

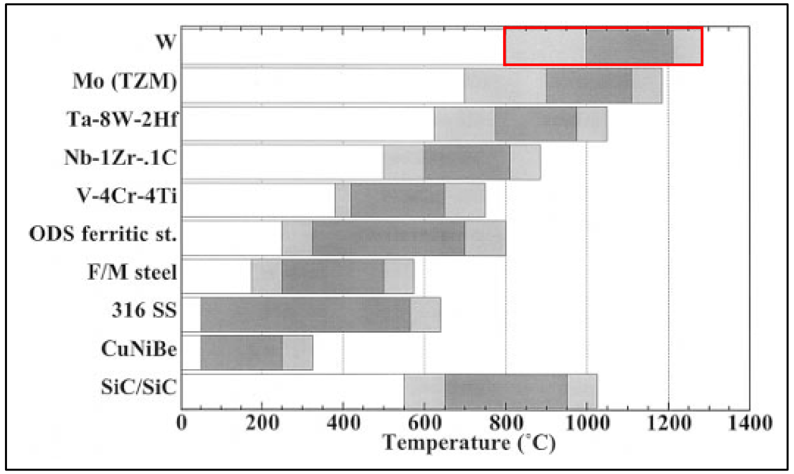
1. Garrison, L.M., et al., Phenix US-Japan collaboration investigation of thermal and mechanical properties of thermal neutron–shielded irradiated tungsten. Fusion Science and Technology, 2019. 75(6): p. 499-509.

Temperature Targets

- Tungsten is currently seen as the most promising near-term material for the first wall and divertor in fusion reactor designs
- Reference values for temperature and heat flux are as follows:
  - First wall heat flux: <1 MW/m^2
  - Divertor heat flux: >10 MW/m^2
  - Tungsten operating temperature window: 800–1300(?)°C



R.J. Kurtz, G. R. Odette, "Overview of Reactor Systems and Operational Environments for Structural Materials in Fusion Reactors", Structural Alloys for Nuclear Energy Applications, pp. 51-102, 2019.



S.J. Zinkle, N.M. Ghoniem, "Operating Temperature Windows for Fusion Reactor Structural Materials", Fusion Engineering and Design, Vol. 51-52, pp. 55-71, 2000.

Neutron Irradiation & Thermomechanical Experiment (NITE)

- Hypothetical ATR experiment that would simultaneously incorporate:
  - Neutron irradiation using a thermal neutron filter (e.g., Gd)
  - Large temperature gradient/ heat flux across a test specimen
  - Prototypic helium production in tungsten
- Use a TRISO compact to generate heat

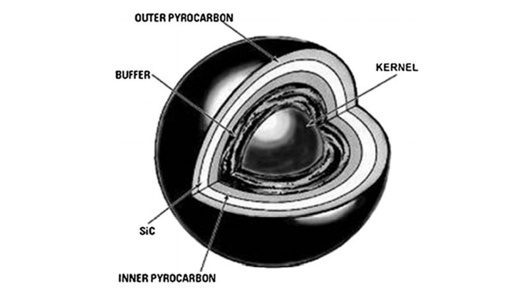
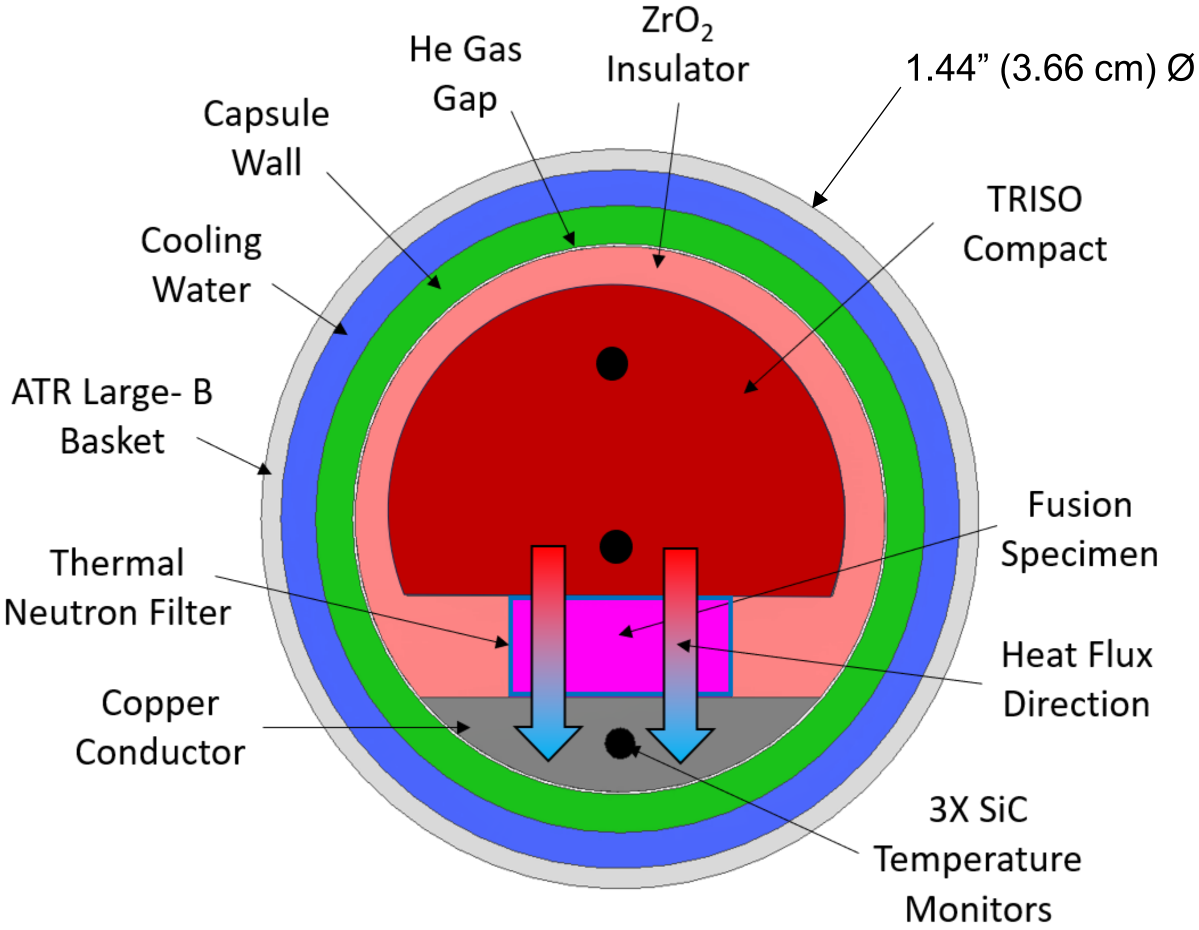


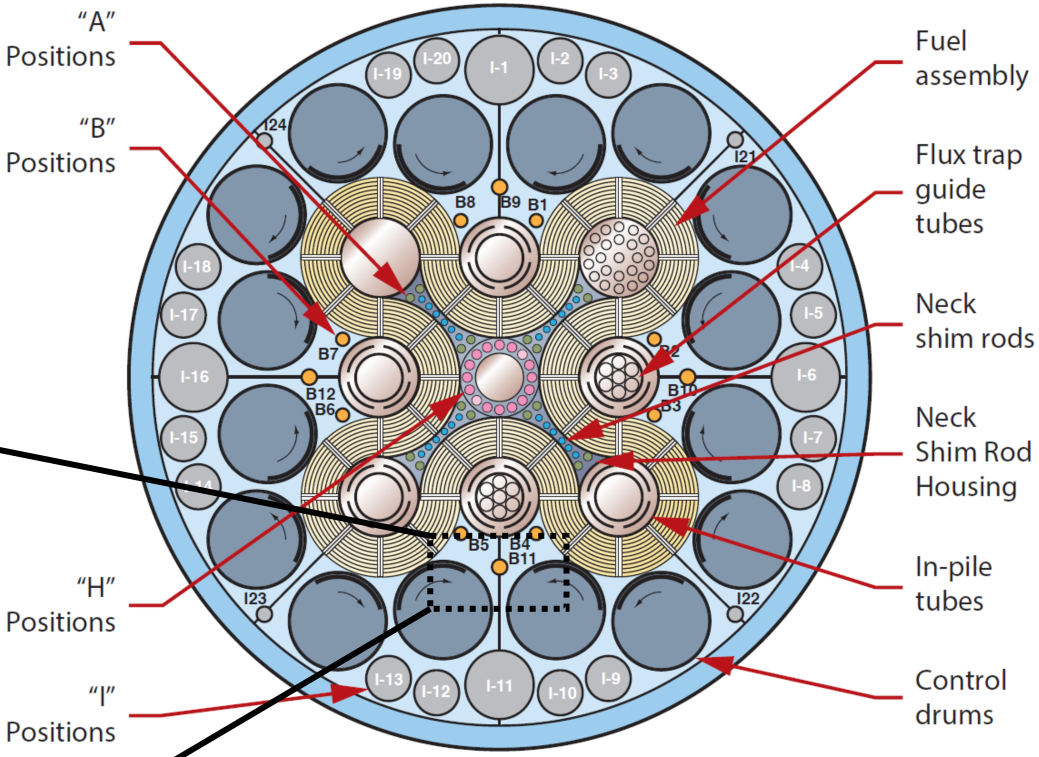
Figure 2.1. HTGR TRISO Coated Fuel Particle (Zhou and Tang 2011)

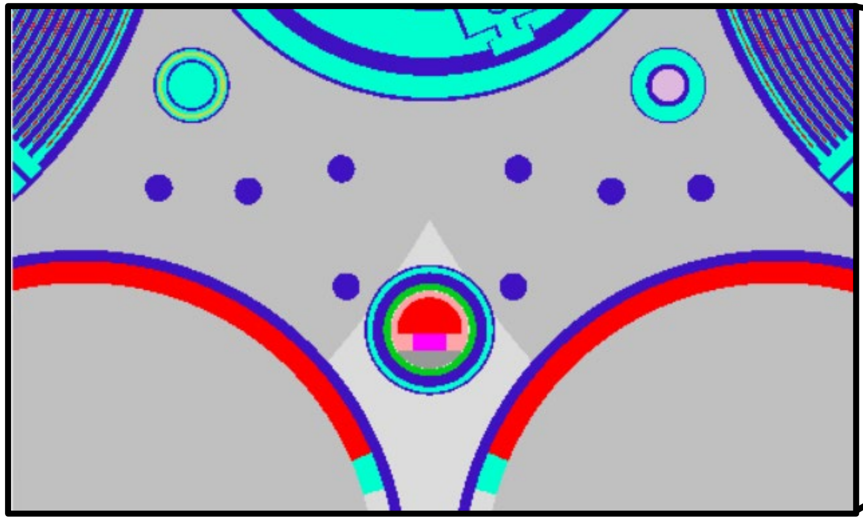


Advanced Test Reactor (ATR) Overview

- 250 MW thermal test reactor located at Idaho National Laboratory
- 70+ experiment positions
- NITE conceptually designed for a large-B position (1.5” diameter)

Figure 2. ATR Core Cross Section.





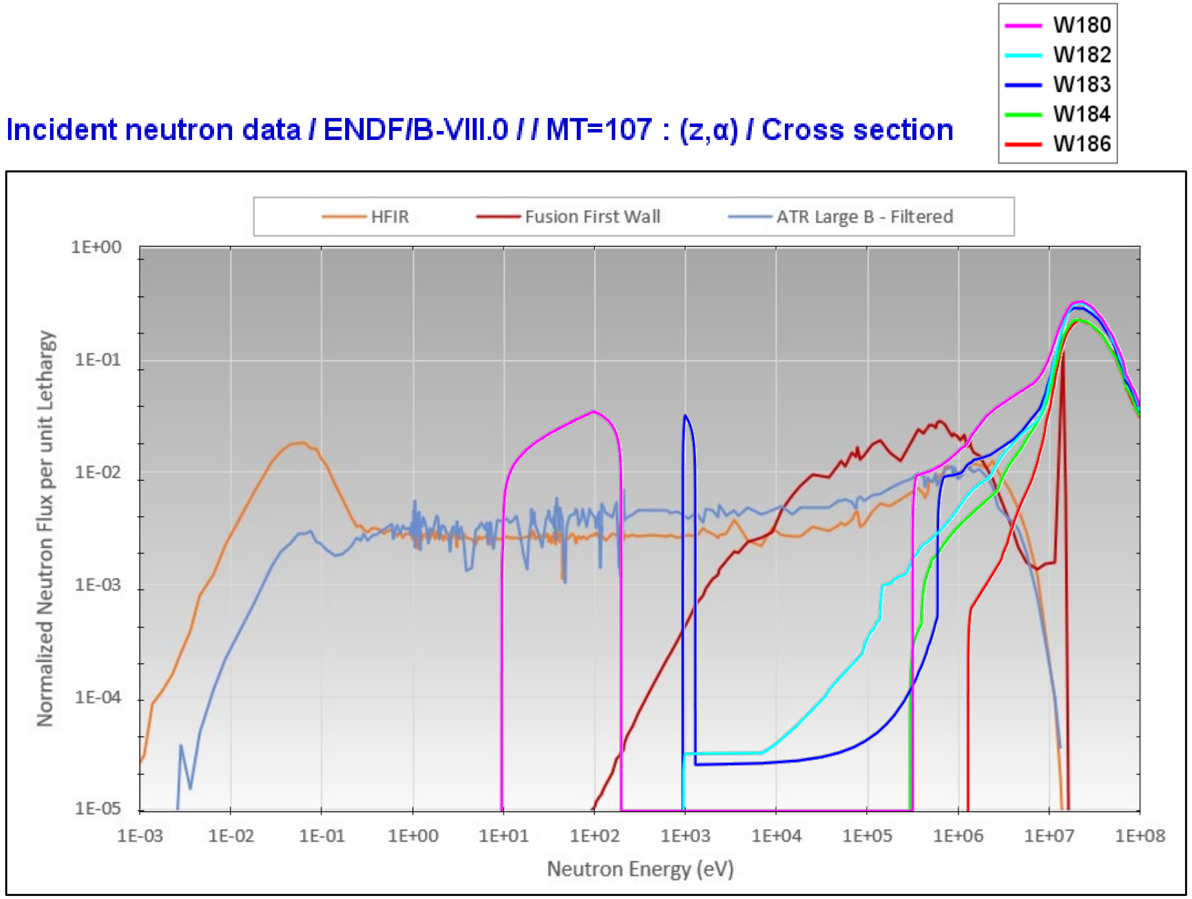
The Problem with Thermal Test Reactors

Element concentration (atoms/b-cm) after irradiation of pure tungsten to a total neutron fluence of 3.5E+21 n/cm^2.

Element	Fusion Spectrum	Filtered ATR Spectrum	% diff	Unfiltered HFIR Spectrum	% diff
W	6.32E-02	6.23E-02	-1.5%	6.18E-02	-2.2%
HF	2.30E-08	3.24E-10	-98.6%	9.37E-10	-95.9%
HE	2.66E-08	3.67E-10	-98.6%	9.80E-10	-96.3%
OS	9.13E-09	2.35E-05	257173.5%	6.18E-05	676981.4%
TA	1.14E-06	2.84E-07	-75.2%	4.41E-07	-61.5%
RE	9.74E-06	9.37E-04	9524.0%	1.32E-03	13498.6%
H	5.18E-08	1.24E-10	-99.8%	0.00E+00	-100.0%

Takeaways:

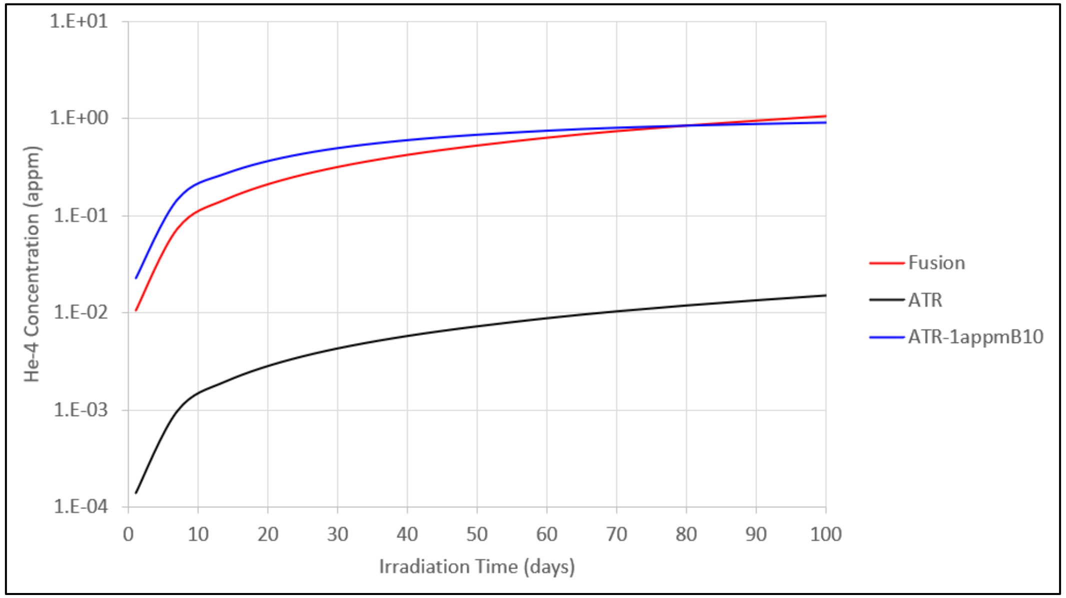
1. Thermal spectrum reactors cannot simulate high-energy (n,alpha) and (n,p) reactions
2. Even with a thermal neutron filter, thermal/epithermal reactions cannot be fully eliminated



Bohm, Tim D.; Davis, Andrew; Harb, Moataz S.; et al., Initial Neutronics Investigation of a Liquid-Metal Plasma-Facing Fusion Nuclear Science Facility
FUSION SCIENCE AND TECHNOLOGY Volume: 75 Issue: 6 Special Issue: SI Pages: 429-437 Published: 2019

Boron Doping to Increase Helium Production

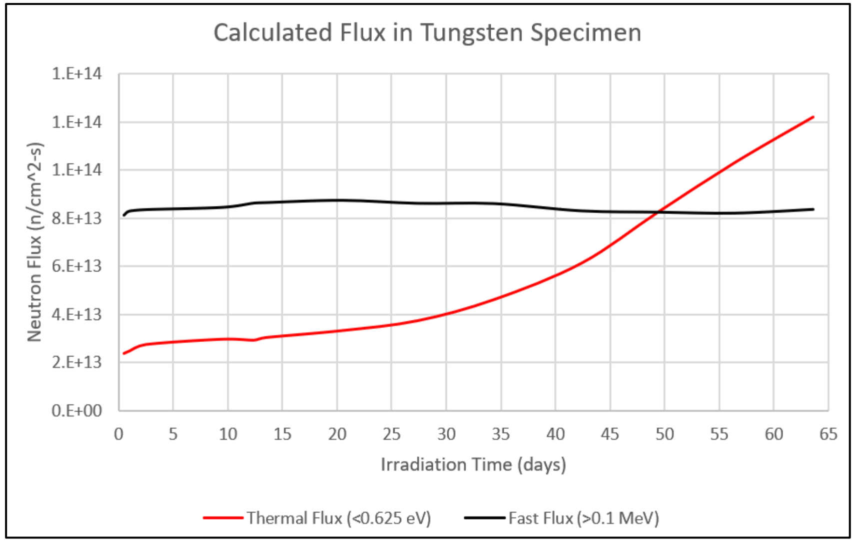
- We can't do much about the rhenium and osmium buildup in tungsten, but we can simulate helium production by using boron as a dopant[1]
  - Helium created via $^{10}B\ (n,\alpha)^{7}Li$
  - Amount of initial B10 can be tailored to match target end-of-life He content
  - Plot below shows effect of 1appm B10 in tungsten

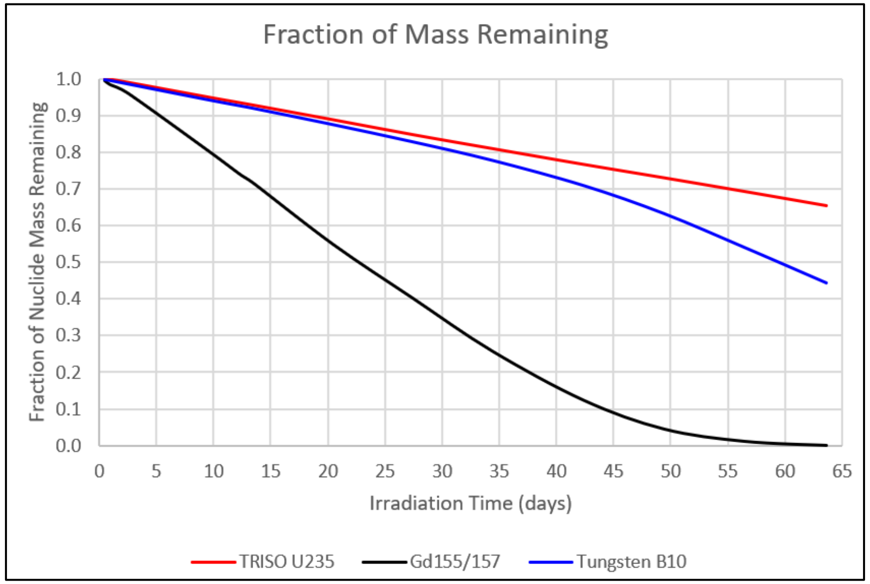


1. Jung Y., Li J., "Boron-10 stimulated helium production and accelerated radiation displacements for rapid development of fusion structural materials", Journal of Materiomics, Volume 10, Issue 2, pp. 277–385, 2024. https://doi.org/10.1016/j.jmat.2023.06.009

Neutronic Results

- TRISO parameters:
  - 400 μm diameter UO_2 kernel
    - 19.75% enriched
  - 810 μm particle diameter
  - 35% packing fraction in graphite
- Test specimen is tungsten with 1 appm B10
- Depletion performed for one ATR cycle
  - Average fast flux (>0.1 MeV): 8.4E+13 n/cm^2-s
  - Beginning-of-life fast to thermal ratio: 3.4
  - Fast fluence (>0.1 MeV): 1.9E+21 n/cm^2/year*
  - Damage: 0.16 DPA/year*



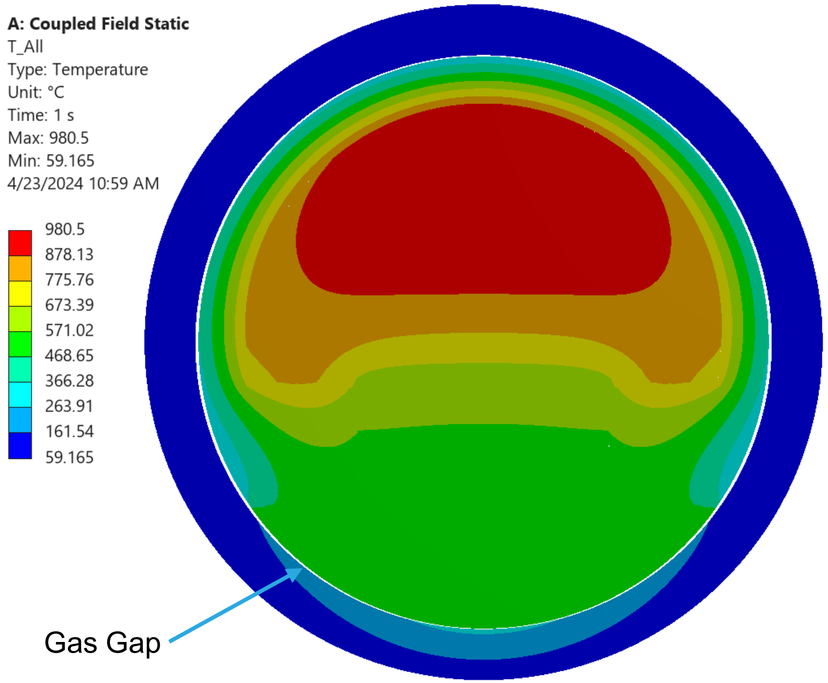


* Assumes four 60-day ATR cycles per year

Thermal Results

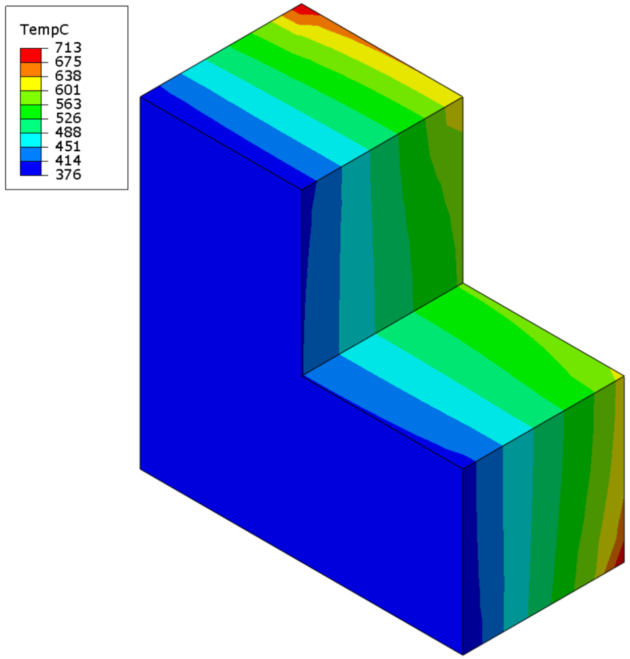
Specimen material: Tungsten
Specimen dimensions: 1cm x 1cm x 0.5cm

TRISO Fuel Heating Rate = 271.2 W/cm^2
Gas Gap = 0.013 cm (0.0053 in)



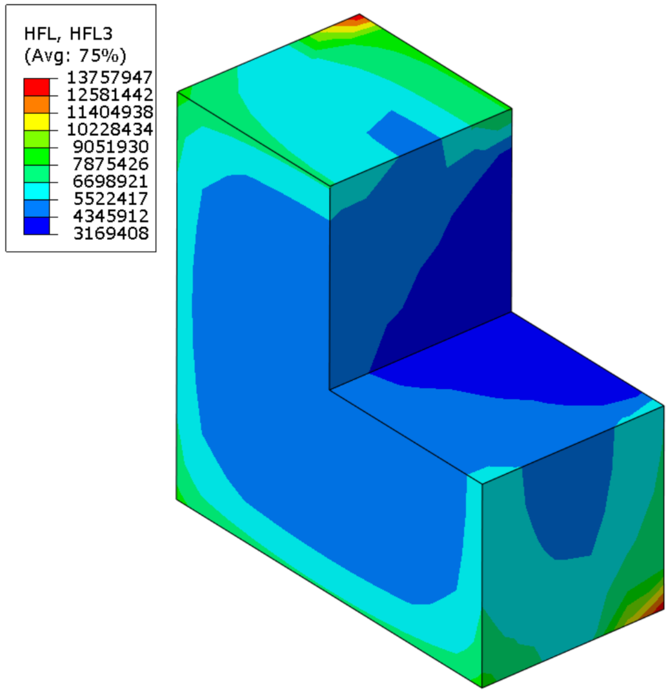
Temperature (°C)

Peak TRISO Temperature: 981°C



Tungsten Temperature (°C)

Avg. Temp: 503 °C
Centerline ΔT: 223°C



Heat Flux (W/m^2)

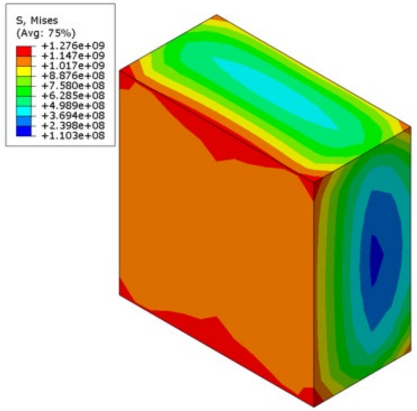
Avg. Heat Flux: 5.0 MW/m^2

Summary

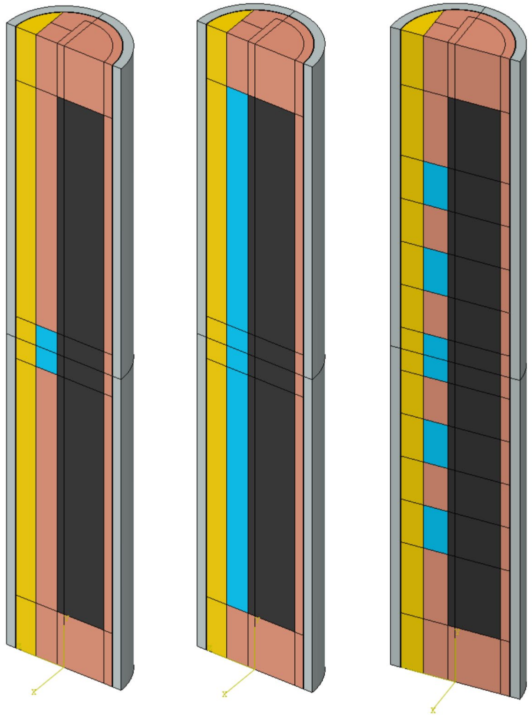
- A concept for a synergistic neutron irradiation and thermomechanical experiment for PFMs in the ATR has been proposed
- Such a test would allow for study of multiple fusion-relevant parameters simultaneously:
  - Average fast neutron flux of 8.4E13 n/cm^2-s
  - Temperature gradient of 223°C across sample
  - Average heat flux of 5.0 MW/m^2
  - Prototypic helium production in tungsten
- Current work utilizes an elemental tungsten target, but could be any fusion-relevant material (e.g., SiC, RAFM steels, vanadium alloys, tungsten HEAs)

Future/Ongoing Work

- Design sensitivities
  - Gd thickness
  - TRISO compact loading
  - 3D thermomechanical effects
- Investigation of alternate geometries
  - Different specimen sizes
  - Alternate specimen loading



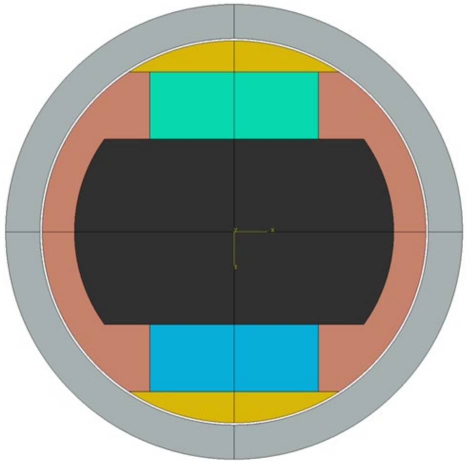
Specimen Stress



Short Specimen

Long Specimen

Multiple Specimens



Double Holder Design

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